

Integrated Detection Method of Underwater Acoustic Fuze Based on IEMD, VIFD and ED

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Abstract

In this paper, in order to solve the problem of accurately detecting the underwater acoustic fuze in the complicated natural interferences, with the different macrostructure and microstructure between the target echo signals and the interferences such as reverberation, a novel integrated detection method of underwater acoustic fuze is proposed, where firstly these different intrinsic mode functions (IMFs) are decomposed via the improved empirical mode decomposition (IEMD) from original signals received by the fuze system, to separate the target echo signal from the reverberation, and secondly the statistics of variance-of-instantaneous-frequency detection (VIFD) and energy detection (ED) are obtained from IMFs and combined as an integrated detector to detect the underwater acoustic fuze excellently. Through lake tests, this method is applied to the underwater acoustic fuze detection, and these testing results show that the proposed method has better detection performance than the traditional detection method, such as energy detection and variance-of-instantaneous-frequency detection.

Keywords

Underwater Acoustic Fuze; Integrated Detection; Improved Empirical Mode Decomposition; Variance of Instantaneous Frequency

Introduction

The background interference of underwater active acoustic fuze system (UAAFS) includes the natural interference, such as the natural noise in marine environment, the radiated noise of underwater vehicles and warships, the ocean reverberation and the wake scattering interference, in addition to the artificial interference, such as a single or series of explosions interference and countermeasure equipment interference. The natural and artificial interference usually be considered in UAAFS [1]. Especially in shallow water and short-range, the reverberation interfering with the target echo signal is

a major interference factor in the echo analysis and processing, where the amplitude of valid target signal may be submerged, so that the target characteristics can't be discriminated from the amplitude of fuze signal [2]. Therefore, it is very important that the target echo features are extracted from the underwater acoustic reverberation, and it is a prerequisite for the subsequent processing of the target echo.

Empirical Mode Decomposition (EMD) can adaptively decompose the complicated multi-component signal into a number of single component signals according to the local characteristic time scales of the signal, where the target signal and the interference signal is broken down into these different intrinsic mode functions (IMF) [3-4]. With the different modal characteristics between the target signal and the interference signal, the local features of the weak target signal can be enhanced. In fact, the modulation characteristic of the transmitted signal is not the same through the underwater target and the surface or seabed, so that for the target signal and the interference signal, there are the essential differences among Doppler frequency, energy and delay [5]. Therefore, in this paper, an improved EMD (IEMD) algorithm based on windowed and adjacent addition IMF is proposed to separate the target echo signal from the reverberation.

Some traditional detection methods, such as match filter detection, correlation detection and energy detection, are usually applied to underwater target echo detection [6-7]. The matched filter detector and the correlation detector are optimal to detect the determinate signal from the white noise background in the ideal channel. Due to the complexity of the underwater acoustic channel and multi-path effects,

the detection performance of the theoretical detector often has a serious decline in practical applications [8]. With the difference of power level (or amplitude) between the target echo signal plus noise and the noise, energy detector is only utilized to detect the change of the input noise amplitude mean which stands for the target signal or the noise, and don't consider the details of echo signal and interference [9]. As a new target detection method with the constant false alarm rate, the variance-of-instantaneous-frequency detection (VIFD) uses the details of the instantaneous frequency and these statistical characteristics of the echo signal and the interference to detect the target from the reverberation, which is independent of the variety of the background interference without the target echo signal [10]. In engineering applications, the single VIFD method needs to be combined with other detection methods to improve the detection and anti-jamming capability.

On the basis of the above discussion, a novel integrated detection method of underwater acoustic fuze based on the IEMD, the energy detector and the VIFD method is proposed, where the validity is verified with the engineering application.

Improved Emd

Blackman windowed EMD (WEMD)

EMD has been pioneered by N.E. Huang et al. for adaptively representing non-stationary signals as sums of different simple intrinsic modes of oscillations [3]. With the EMD method, a signal could be decomposed into a number of Intrinsic Mode Functions (IMFs), each of which must satisfy the two definition: (1) In the whole data set, the number of extrema and the number of zero-crossings must either equal or differ at most by one. (2) At any point, the mean value of the envelope defined by local maxima and the envelope defined by the local minima is zero.

With a series of sifting, any signal $x(t)$ can be decomposed with EMD as follows

$$x(t) = \sum_{i=1}^n f_i(t) + r_n(t) \quad (1)$$

Thus, one can achieve a decomposition of the signal into n -IMFs and a residue. The IMFs $f_i(t)$ and residue $r_n(t)$ include different frequency bands ranging from high to low. The EMD techniques provide a multi-scale analysis of the signal as a sum of orthogonal

signals corresponding to different time scales.

In order to reduce or eliminate endpoint effects in application of EMD method, a new boundary processing method based on Blackman window is presented [11]. With this method, the analyzed signal $x(t)$ is preprocessed by multiplying with the defined window function $w(t)$, so that the amplitudes of the signal remain in middle and reduce in both ends. Then, EMD is used to analyze the preprocessed signal $\bar{x}(t) = w(t)x(t)$. According to Eq. (1), $\bar{x}(t)$ can be defined as

$$\bar{x}(t) = \sum_{i=1}^n \bar{f}_i(t) + \bar{r}_n(t) \quad (2)$$

So we can obtain the reconstruct function of the Blackman windowed EMD method as

$$x(t) = \sum_{i=1}^n \frac{\bar{f}_i(t)}{w(t)} + \frac{\bar{r}_n(t)}{w(t)} \quad (3)$$

Also take the lake-test echo signal as an example in Fig. 1, and the decomposed results with the proposed method are shown in Fig. 2. With the statistical analysis, the ratios of the sum of the first four IMFs' energy to original signal's energy are more than 99%. So we only consider the first four IMFs $f_1 \sim f_4$ in Fig. 2, where it is obvious that the proposed boundary processing method sacrifices a few end points but protects the most middle points of the signal from being "polluted".

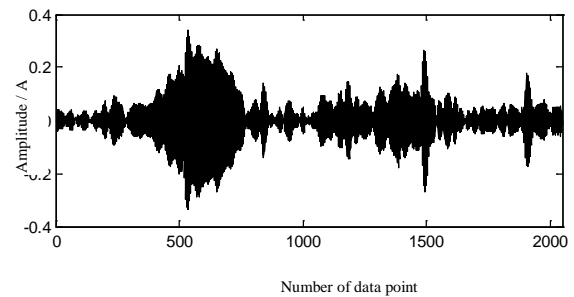


FIG. 1 THE ACTUAL UNDERWATER ECHO SIGNAL

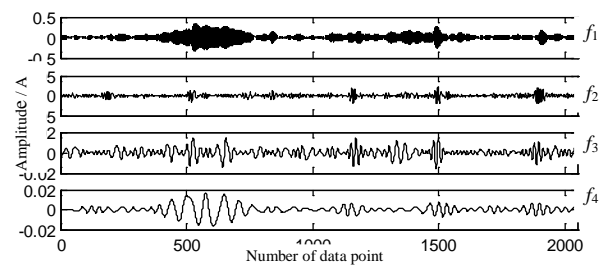


FIG. 2 THE IMFS WITH WINDOWED EMD

The joint processing method with windowed and adjacent addition EMD

In Fig. 2, the experimental studies verified that the windowed EMD method can enormously decrease the boundary distortion. However, our research shows that sometimes noise will increase the EMD error so greatly that the IMFs are distorted seriously and fail to illustrate the actual modes involved in the signal. In order to solve the problem that the characteristic information of an intrinsic oscillation mode is split into two or more intrinsic mode functions, the joint processing method with windowed and adjacent addition EMD is proposed to increase the precision of EMD.

The proposed joint processing method is based on the following three steps:

1) Compute the instantaneous frequency (IF) $\omega(t)$ of every IMF via the windowed EMD. For one IMF $f_i(t)$ in Eq. (3), we can always have its Hilbert transform as

$$H[f_i(t)] = \frac{1}{\pi} P \int_{-\infty}^{\infty} \frac{f_i(\tau)}{t - \tau} d\tau \quad (4)$$

where P means the Cauchy principal component. Then we can have an analytic signal as

$$A[f_i(t)] = f_i(t) + jH[f_i(t)] = a_i(t)e^{j\theta_i(t)} \quad (5)$$

with $a_i(t) = \sqrt{f_i^2(t) + H^2[f_i(t)]}$, $\theta_i(t) = \arctan[\frac{H[f_i(t)]}{f_i(t)}]$. So the IF

$\omega_i(t)$ can be expressed as

$$\omega_i(t) = \frac{d\theta_i(t)}{dt} \quad (6)$$

2) Consider the adjacent IMFs using a rectangular sliding time window. If their IFs change suddenly during the same period, the adjacent IMFs should be added to form the new IMFs $Cf_k(t)$.

3) Together make up the real IMFs with the new $Cf_k(t)$ and the residual $f_i(t)$.

In order to verify the effectiveness of the joint processing method with windowed and adjacent addition EMD, the lake-test echo signal in Fig. 1 is analyzed, and the four IFs $\omega_1 \sim \omega_4$ in Fig. 3 are obtained with Eq. (6), corresponding to the four IMFs $f_1 \sim f_4$ in Fig. 2.

Compared Fig. 2 with Fig. 3, it can be seen that the relative IF ω_1 changes smoothly and its value is maximum among these IFs $\omega_1 \sim \omega_4$. The value of ω_1 is consistent with the Doppler frequency of underwater

target, so the IMF f_1 stands for the target echo signal (corresponding to Cf_1 in Fig. 4).

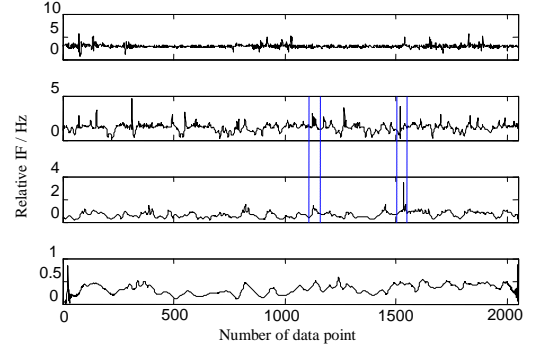


FIG. 3 THE INSTANTANEOUS FREQUENCIES WITH WINDOWED EMD

Due to the interference effects of intermittence and reverberation, the echo signal of the interface reverberation is broken down into $f_2 \sim f_3$, and the decomposition process is distorted. According to the above three steps of the proposed joint processing approach, the IFs ω_2 and ω_3 are processed to judge whether these IFs change suddenly via the rectangular window sliding along the time axis with a length of 50 data points (see the two dotted lines in Fig. 3). It can be seen that ω_2 and ω_3 change suddenly in the window between 1130-point and 1518-point. So the adjacent IMF f_2 and f_3 should be added to form the new IMF, $Cf = f_2 + f_3$ (corresponding to Cf_2 in Fig. 4). The last IF ω_4 shows that f_4 is a slowly varying echo envelope component, and the envelope length around 550-point coincides with the pulse width of the target echo, which indicates that f_4 is the target echo envelope component (corresponding to Cf_3 in Fig. 4). Therefore, with windowed and adjacent addition EMD method, these IMFs $Cf_1 \sim Cf_3$ are shown in Fig. 4, which stand for the target echo, the reverberation and the target echo envelope component, respectively.

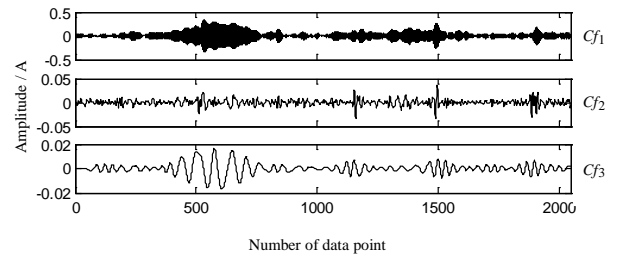


FIG. 4 THE IMFS WITH WINDOWED AND ADJACENT ADDITION EMD

In fact, the modulation characteristic of the transmitted signal is not the same through the

underwater target and the surface or seabed, so that for the target signal and the interference signal, there are the essential differences among Doppler frequency, energy and delay.

In theory, due to the different mode characteristics between the echo of the underwater target acoustic fuze and the reverberation, and the different modulation characteristic of the transmitted signal between the underwater target and the surface, there are essential differences between the underwater target echo and the reverberation received by UAAFS in the Doppler frequency, energy, delay, etc. So the IMFs of the underwater target acoustic fuze signal can be extracted from the reverberation via the proposed joint processing method.

Conventional Detection Methods for Underwater Acoustic Fuze

Energy detector

The energy detector can be expressed as the following binary detection [6]:

$$\begin{aligned} H_0 : x[i] &= n[i] & i &= 0, 1, \dots, N-1 \\ H_1 : x[i] &= s[i] + n[i] & i &= 0, 1, \dots, N-1 \end{aligned} \quad (7)$$

where H_0 denotes that the receiving underwater acoustic signal is only the reverberation interference, and H_1 denotes that the receiving underwater acoustic signal contains the underwater target echo and the reverberation, with $x[i]$ for the receiving underwater acoustic signal, $s[i]$ and $n[i]$ for the target signal and the interference, respectively.

According to the Neyman-Pearson detection criteria, the energy detection statistic (EDS) $E(x)$ can be expressed as follows

$$E(x) = \sum_{i=0}^{N-1} x^2(i) / \sigma_n^2 \begin{matrix} H_1 \\ > r' \\ H_0 \end{matrix} \quad (8)$$

where $\sum_{i=0}^{N-1} x^2(i)$ is the energy and σ_n^2 is the variance of the underwater acoustic signal $x[i]$. Comparing $E(x)$ with detection threshold r' and taking the result as the basis of judgment, we have the intuitive conclusion that $E(x)$ will increase when $x[i]$ contains the fuze target echo.

Corresponding to these new IMFs $Cf_1 \sim Cf_3$ in Fig. 4, these normalized test statistics of energy detection in Fig. 5 are calculated according to the sliding time

window with the same length to the transmitting pulse width. For Cf_1 , the maximum EDS (750-point) is 2.5dB higher than the second-largest EDS (1518-point), and for Cf_3 , the maximum EDS (750-point) is 4.8dB higher than the second-largest EDS (1750-point), which shows that the underwater target can be detected with the target echo signal Cf_1 or the target echo envelope component Cf_3 .

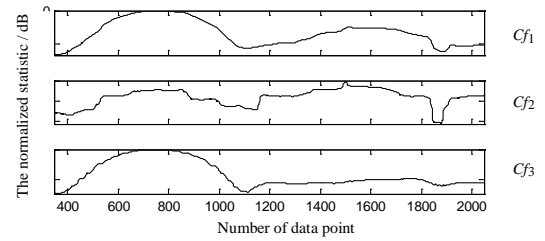


FIG. 5 THE NORMALIZED TEST STATISTICS OF ENERGY DETECTION

Variance-of-instantaneous-frequency detection

The mean of the instantaneous frequency of the single-frequency signal plus interference noise (SFSPIN) is the carrier frequency, and its instantaneous frequency variance can be expressed as [10]:

$$\sigma_f^2 \approx \frac{q}{(q+1)^2} (f_0 - f_1)^2 + \frac{W^2}{12(q+1)} \quad (9)$$

where q is the signal to noise ratio, f_0 is center frequency, f_1 and w stand for the center frequency and bandwidth of SFSPIN. It can be seen that σ_f^2 is a monotonically decreasing function with q , so we can take the real-time $1/\sigma_f^2$ as the VIFD statistics (VIFDS), and compare $1/\sigma_f^2$ with the detection threshold r'' via binary detection. The target echo signal will appear when $\sigma_f^2 > r''$, and the reverberation or the noise interference noise interference $\sigma_f^2 \leq r''$.

Though finding the starting point of this instantaneous frequency variance sequence when $\sigma_f^2 > r''$, we can extract the target echo from the various noise interference, and thus construct the detector $IF(x)$ of VIFD.

These normalized test statistics of VIFD in Fig. 6 are calculated according to the sliding time window with the same length to the transmitting pulse width, corresponding to $Cf_1 \sim Cf_3$ in Fig. 4.

In Fig. 6, the test results of VIFD are similar to EDS in Fig. 5. For Cf_1 , the maximum VIFDS is 2.2dB higher than the second-largest VIFDS, and for Cf_3 , the

maximum VIFDS is 0.9dB higher than the second-largest VIFDS. From the Fig. 5 and Fig. 6, it can be seen that the underwater target can be detected with the target echo signal Cf_1 using EDS or VIFDS. However for Cf_3 , the testing performance of EDS is inferior to the VIFDS', because the frequency is lower and the waveform changes slowly, where the detailed varieties of VIFDS are not so obvious.

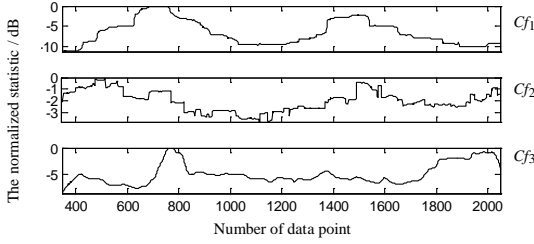


FIG. 6 THE NORMALIZED STATISTICS OF VIFD

Integrated Detection Method for Underwater Acoustic Fuze

On the basis of discussion above, energy detector is suitable to detecting the change of the energy mean of the target signal or the noise, and don't consider their details. On the contrary, VIFD is applied on detailed observations of IF of the echo signal and the interference to detect the target from the reverberation. So this paper presents a novel integrated detection method, where energy detector and VIFD are combined to improve the detection performance of a single detector with the macro and micro information.

The structure of integrated detection (ID) method is as shown in Fig.7, where these new adjacent addition IMFs are decomposed from the received acoustic fuze data via the joint processing method with windowed and adjacent addition EMD, and VIFDS IF_i and EDS E_i are obtained from these above IMFs. Thus the test statistics of the ID method can be shown as

$$\lambda_i = \frac{E_i}{IF_i} \quad (10)$$

Assuming the probability of false alarm and the detection threshold r , we have the detection results via binary detection: H_1 comes into existence and the target will appear when $\lambda_i > r$; and H_0 exists and there is no a target r when $\lambda_i \leq r$. So the ID system for underwater acoustic fuze can be built to detect the underwater target optimally.

With the ID method, these normalized test statistics λ_i are shown in Fig. 8, corresponding to $Cf_1 \sim Cf_3$ in Fig. 4, where for Cf_1 , the maximum test statistic is 7.2dB

higher than the second-largest, and for Cf_3 , the maximum is 11.6dB higher than the second-largest. Comparing Fig. 8 with Fig. 5 and Fig. 6, it can be seen that for Cf_1 , the detection gain of the ID method is about 5dB higher than the single method's, and for Cf_3 , the detection gain is 7~11dB higher than the single method's, which indicates that the ID method combines these advantages of ED and VIFD, and has a better detection performance.

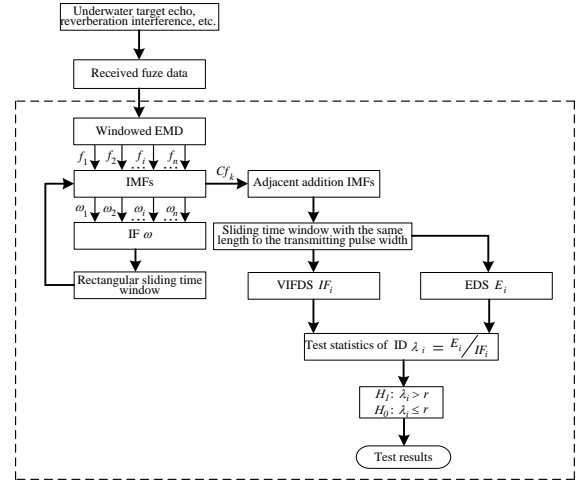


FIG. 7 THE FLOW CHART OF ID FOR UNDERWATER ACOUSTIC FUZE

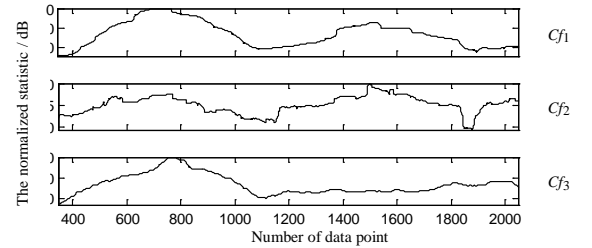


FIG. 8 THE NORMALIZED STATISTICS OF ID

Engineering Applicaitons

In order to verify the detection ability and validity, we take the lake-test fuze echo signal of underwater acoustic target for example, and compare the performance of the integrated detection method with ED and VIFD. The received lake-test fuze echo signal in a received cycle is shown in Fig. 9.

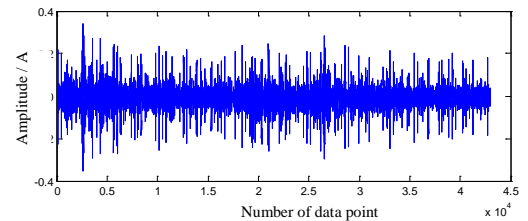


FIG. 9 THE ACTUAL UNDERWATER ECHO SIGNAL WITHIN ACOUSTIC PERIOD

The adjacent addition IMF c_{f_1} is obtained from the echo signal in Fig. 9 via the joint processing method with windowed and adjacent addition EMD, and the normalized test statistics (the maximum test statistics are 0dB) are calculated and shown as in Fig. 10 through ED, VIFD and ID. And for the three types of detection method, the mean and the second-largest statistics have been listed in Table 1.

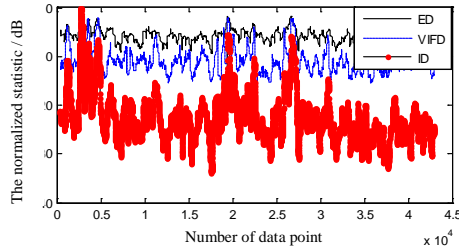


FIG. 10 THE NORMALIZED STATISTICS OF THREE DETECTION METHODS

TABLE 1 THE PERFORMANCE COMPARISON OF THREE ACOUSTIC FUZE DETECTION METHODS

Type of detection method	The test statistics (dB)	
	Mean	Second-largest
ED	-5.8	-1.7
VIFD	-10.9	-2.1
ID	-22.5	-5.6

It can be seen from Fig. 10 and Table 1 that for ID method, the test statistic when the target appears is about 22.5dB higher than the average of reverberation's, and the detection gain increase to 16.7 dB and 11.6 dB respectively, compared with ED and VIFD. It indicates that the detection performance of ID is greatly improved, and its inhibitory effect for the interference noise (the second-largest test statistic) is better than ED and VIFD.

In addition, the number of data point is labeled as P when the value of test statistic is equal to 0, which indicates that the target appears. And the time delay from the target to the received platform can be shown as $\hat{\tau} = P / f_s$, where f_s is the sampling frequency. So the distance \hat{R} between the target and the acoustic fuze received platform can be shown as

$$\hat{R} = \frac{\hat{\tau}c}{2} \quad (11)$$

Through lots of experiments, the calculation results show that the estimated distances \hat{R} agreed with the practical conditions.

Moreover, we took a large number of underwater acoustic echo signals as testing samples to detect the

underwater target, and found that the ID method has more macro and micro information than ED and VIFD, with combining the advantages of ED and VIFD. All these indicate that the ID method has more capacity of reliability and robustness, and holds significant promise in the acoustic fuze detection for the underwater moving target.

Conclusions

In this paper, a novel integrated detection (ID) method of underwater acoustic fuze based on IEMD, viz., the joint processing method with windowed and adjacent addition EMD, energy detection (ED) and variance-of-instantaneous-frequency detection (VIFD) is proposed. The proposed method is applied to the underwater acoustic fuze detection, and these testing results are shown as following:

- 1) The improved EMD method based on the windowed EMD and the adjacent addition EMD can enormously decrease the boundary distortion and over-decomposition phenomena effectively, and has a better decomposition ability, compared with the conventional EMD method. And the IEMD can decompose the target echo signal from the reverberation interference, due to the different mode characteristics between the target echo and the reverberation, and the different modulation characteristic of the transmitted signal between the underwater target and the surface.
- 2) The ID method has more capacity of anti-interference, reliability and robustness than the single ED or VIFD method, and holds significant promise in the acoustic fuze detection for the underwater moving target.

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REFERENCES

- [1] X.Chen, T. Jiang,X. F. Li, Implementation of On-land Simulation of Torpedo Active Ultrasonic Fuze. *Torpedo Technology*, 16(5):34-37(2008).
- [2] S. G. Chamberlain, J. C. Galli, A Model for Numerical Simulation of Nonstationary Sonar Reverberation using Linear Spectral Prediction. *IEEE Journal of Oceanic Engineering*, 8(1):21-36(1983).

- [3] N. E. Huang, Z. Shen, S. R. Long, a New View of Nonlinear Water Waves: the Hilbert Spectrum. *Annual Reviews of Fluid Mechanics*, 3:417-457(1999).
- [4] Q. Hu, B. A. Hao, L. X. Lv, et al, Hybrid Intelligent Detection for Underwater Acoustic Target Using EMD, Feature Distance Evaluation Technique and FSVDD, *International Congress on Image and Signal Processing* (2008), IEEE,5(4): 54-58.
- [5] V. Carmillet, P. O. Amblard, G. Jourdain, Detection of Phase- or Frequency- Modulated Signals in Reverberation Noise . *Journal of the Acoustical Society of America*, 105(6):3375-3389(1999).
- [6] M. K. Steven, *Fundamentals of Statistical Signal Processing, Volume II: Detection Theory*, Pearson Education Publishers, Prentice Hall PTR (1998).
- [7] H. C. Song, W. S. Hodgkiss, W. A. Kuperman, Experimental Demonstration of Adaptive Reverberation Nulling using Time Reversal . *Journal of the Acoustical Society of America*, 118(3):1381-1387(2005).
- [8] D. H. Chambers, J. V. Candy, S. K. Lehman, Time Reversal and the Spatial-temporal Matched Filter. *Journal of the Acoustical Society of America*, 116(3):1348-1350(2004).
- [9] V. I. Kostylev, Energy Detection of A Signal with Random Amplitude. *IEEE International Conference on Communication* (2002), Russia:Voronezh,, 3(2):1606-1610.
- [10] G. L. Liang, Study on Transient Parameter Sequence of Echoed Signal and its Application. Harbin Engineering University doctoral dissertation (1997).
- [11] Q. Hu, B. A. Hao, L. X. Lv, et al, Feature Extraction Model for Underwater Target Radiated Noise. *Torpedo Technology*, 16(6):38-43(2008).



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